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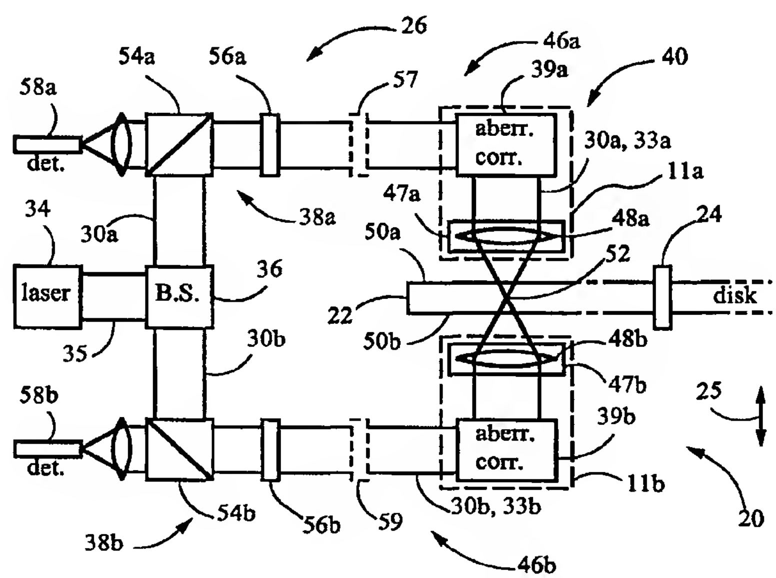
(54) Title: MULTILAYER REFLECTION MICROHOLOGRAM STORAGE

(57) Abstract

Digital data bits are stored as discrete-level reflection microholograms in a multi-depth digital optical data storage system (20). Reference and signal beams are incident in a counterpropagating geometry on opposite faces of a homogeneous photopolymer disk medium (22). The reflection microholograms are stored at the coinciding focus of the reference and signal beams. The holograms are stored at the diffraction limit of high-N.A. optics (46a-b), and have relatively high grating frequencies and small sizes. Dynamic aberration compensators (39a-b) correct for the depth-varying spherical aberration imparted to the beams by the medium. Multiple mutually-incoherent lasers are used for parallel storage and retrieval to increase data transfer rates. Achievable densities and signal-to-noise ratios are substantially higher than for index-perturbation or transmission hologram storage methods.



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Multilayer Reflection Microhologram Storage

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority from US Patent application no. 09/016,213 filed 30 January 1998.

FIELD OF THE INVENTION

The present invention relates to the field of holographic data storage, and in particular to a system and method for storing digital data as reflection microholograms at a plurality of depths within a holographic storage medium.

BACKGROUND OF THE INVENTION

In holographic storage, data is stored in a hologram resulting from the interference of a signal and reference beam. During storage, both the reference and signal beams are incident on the storage medium. During retrieval, only the reference beam is incident on the medium. The reference beam interacts with the stored hologram, generating a reconstructed signal beam proportional to the original signal beam used to store the hologram. Relative to conventional magnetic and optical data storage methods, holographic data storage promises high storage densities, short access times, and fast data transfer rates. The widespread use of holographic data storage has been hindered by the relative complexity of the specialized components required for storage and retrieval of data.

For information on conventional volume holographic storage see for example U.S. Patent Nos. 4,920,220, 5,450,218, and 5,440,669. In conventional volume holographic storage, each bit is stored as a hologram extending over the entire volume of the storage medium. Multiple bits are encoded and decoded together in pages, or two-dimensional arrays of bits. Multiple pages are stored within the volume by angular, wavelength, phase-code, or

related multiplexing techniques. Each page can be independently retrieved using its corresponding reference beam. The parallel nature of the storage approach allows high transfer rates and short access times, since as many as 10^6 bits within one page can be stored and retrieved simultaneously. Conventional volume holographic storage generally requires complex, specialized components such as amplitude and/or phase spatial light modulators.

In U.S. Patent No. 4,458,345, Bjorklund et al. describe a bit-wise volume holographic storage method using signal and reference beams incident on a rotating disk in a transmission geometry. The signal and reference beams are incident from the same side of the disk. The angle between the reference and signal beams can be altered to store holograms at various depths within the medium. A separate photodetector is used to retrieve data stored at each depth. The interaction of light with the medium is localized through two-photon recording.

In U.S. Patent No. 5,659,536, Maillot et al. describe a system in which multiple holograms are stored at each location in a disk through wavelength multiplexing. Each hologram spans the depth of the medium. In U.S. Patent No. 5,289,407, Strickler et al. describe a multi-layered, non-holographic, index-perturbation optical storage system. Bits are stored as localized perturbations in the index of refraction of a photopolymer, caused by the high intensity at the focus of a single laser beam.

SUMMARY OF THE INVENTION

Briefly, and in general terms, the present invention provides a bit-wise holographic data storage and/or retrieval system and method having improved storage density, and in which the optical components used for storage and retrieval can be relatively simple and inexpensive. With the present invention, bits are stored in a relatively small volume, and in particular over a small depth, as reflection microholograms. Multiple microholograms are stored at a plurality of depth locations, thereby allowing the storage of multiple data layers in a homogeneous medium.

Microhologram storage is accomplished by use of a tunable-focus optical system which focuses a reference beam and a signal beam at a plurality of selected storage locations within the holographic medium. Coincidentally focused reference and signal beams are used in a counterpropagating geometry to record holograms at a plurality of depths. Microhologram retrieval is accomplished by selectively focusing a reference beam on various microholograms recorded at a plurality of depths within the medium, and by capturing the signal beams reflected by the microholograms with an optical detector. By using a tunable-focus reference beam and a counterpropagating beam geometry, a single detector can be used for retrieving data stored as microholograms at a plurality of depths within the medium.

High-numerical-aperture (N.A.) writing and readout heads can be used to enhance the depth localization of the microholograms. Dynamic aberration-correction optics allow the use of the high-N.A. heads over relatively large depths. Storage and retrieval can be achieved in a moving medium such as a rotating disk.

In a presently preferred embodiment, by way of example and not necessarily by way of limitation, the holographic digital data storage system comprises a disk-shaped holographic storage medium, a light source for generating a signal beam and a reference beam, and a tunable-focus storage head system in optical communication with the light source and facing the medium. The storage head system preferably comprises a tunable-focus reference head for focusing the reference beam at storage locations at a plurality of depths within the medium, and a tunable-focus signal head for focusing the signal beam at the same storage locations. The signal and reference heads face the medium on opposite sides. At each location, the reference and signal beams are focused coincidentally, and such that the two beams are counterpropagating. Digital data is stored as reflection microholograms (or microlocalized holographic gratings) resulting from the interference of the signal and reference beams at their foci.

More generally, data can be stored as micro-localized variations in the complex (i.e. real and/or imaginary) index of refraction characterizing reflection holograms. The variations can be represented as complex functions, which functions may be further characterized by a phase. Suitable holograms may include, by way of example and not necessarily by way of limitation: microlocalized variations in the real component of the index of refraction, or microlocalized variations in the amplitude of the index of refraction. Such holograms may also represent data in their relative phases.

A presently preferred retrieval system comprises a medium, a light source, a tunable-focus retrieval head system in optical communication with the light source and facing the medium, and an optical detector in optical communication with the retrieval head. The retrieval head system focuses an input reference beam on reflection microholograms at a plurality of depths within the medium, and captures a reconstructed output signal beam reflected by the holograms. The detector detects the signal beam, for retrieving digital data stored as the holograms. In the preferred embodiment, the retrieval system comprises a single retrieval head.

The storage medium is preferably a homogeneous photopolymer layer. Dynamic aberration compensators are preferably situated in the optical paths between the light source and the retrieval and/or reference/signal storage heads, for compensating for the depth dependences of the spherical aberrations introduced in the signal and reference beams by the storage medium.

In an alternative embodiment, the light source comprises a plurality of mutually incoherent lasers for generating corresponding signal and reference beams. The lasers are arranged so as to be imaged onto the medium along a radial line such that each of the lasers illuminates a different track within the medium.

Other features and advantages of the invention will become apparent from the following detailed description, taken in

conjunction with the accompanying drawings, which illustrates by way of example the invention.

DESCRIPTION OF THE FIGURES

Fig. **1-A** shows a perspective view of a preferred multi-layer reflection microhologram storage system of the present invention.

Fig. **1-B** shows a schematic view of the optical components of a preferred storage system of the present invention.

Fig. **1-C** shows a side schematic view of the optical components of a preferred retrieval system of the present invention.

Fig. **2-A** shows an enlarged schematic side view of a microreflection hologram stored at the focus of counterpropagating beams incident from opposite sides of a storage medium, according to the present invention.

Fig. **2-B** is an enlarged cross-sectional view of a storage medium illustrating a typical arrangement of multiple microhologram layers in a system of the present invention.

Fig. **3** schematically illustrates two adjacent reflection microholograms having opposite phases.

Fig. **4** shows a perspective view of an alternative storage system of the present invention.

DETAILED DESCRIPTION

Preferred Hardware

Fig. **1-A** shows a perspective view of a presently preferred multi-depth reflection microhologram storage/retrieval system **20** of the present invention. System **20** is the preferred embodiment for storage, and can also be used for retrieval. A disk-shaped storage device **21** comprises medium **22** as well as packaging elements for mechanically protecting medium **22** and for mounting device **21** onto holder **24**. Device **21** is detachably mounted on a rotary holder **24**. Holder **24** is controlled by a spindle mechanism to continuously rotate medium **22** at high angular velocity about an axis of rotation **25** coinciding with the depth of medium **22**.

Medium **22** is formed of a structurally homogeneous planar layer of a photopolymer having a thickness preferably on the order of

hundreds of µm, for example about 100-200 µm or less. For information on photopolymers see for example Lessard and Manivannan (ed.), Selected Papers on Photopolymers, SPIE Milestone Series, v. MS-114, SPIE Optical Engineering Press, Bellingham, Washington, 1995. Multiple layers (preferably >5) of concentric data tracks **23** are stacked along the depth of medium **22**. Adjacent data tracks at one depth are separated along a radial direction **15**, while microholograms along a data track are separated along a circumferential direction **17**.

A head/arm assembly **10** is used to access microholograms at storage locations within medium **22**. Head/arm assembly **10** and holder **24** are connected to a fixed housing (not shown). Head/arm assembly **10** comprises carriage assemblies **11a-b**, which are movably mounted on fixed, generally radial, mutually parallel rails **12a-b**, respectively. Carriage assemblies **11a-b** are capable of linear motion along rails **12a-b** along a generally radial direction relative to medium **22**. Carriage assemblies **11a-b** each comprise voice coil actuators for controlling their coarse tracking positionings along rails **12a-b**, with respect to medium **22**. Carriage assemblies **11a-b** face opposite (top and bottom) sides of medium **22**. Carriage assemblies **11a-b** comprise respectively the movable parts of optical heads **46a-b**, as illustrated in Fig. **1-B**. Faces **13a-b** of carriage assemblies **11a-b** provide for optical communication between the optical components mounted on carriage assemblies **11a-b** and fixed optical components mounted outside carriage assemblies **11a-b**. Such fixed components include the fixed parts of optical heads **46a-b** and a light source **34**.

Fig. **1-B** shows a schematic side view of system **20**, illustrating its optical components. Optics **26** for generating a reference beam **30a** and a signal beam **30b** are mechanically coupled to holder **24** such that beams **30a-b** are positioned to coincidentally access medium **22** in a counterpropagating geometry when medium **22** is mounted on holder **24**. Optics **26** comprise a number of components in mutual optical communication: a light source **34** and beam splitting components **36** for generating beams **30a-b**, and a tunable-focus storage head system **40** for directing and

focusing beams **30a-b** onto desired storage locations within medium **22**.

Light source **34** generates a primary light beam **35** which is split by beam splitting components **36** into reference beam **30a** and signal beam **30b**. Components **36** are illustrated schematically in Fig. **1-B**; suitable beam splitting components are well known in the art. Optics **26** are designed such that the optical path difference between beams **30a, 30b** is much less (e.g. <10%, preferably <1%) than the coherence length of light source **34**, such that beams **30a, 30b** are mutually coherent at their coincident foci. Likewise, the coherence length of light source **34** is much larger than the depth over which microholograms are stored.

Head system **40** focuses reference beam **30a** and signal beam **30b** coincidentally at storage locations at a plurality of depths within medium **22**. Head system **40** comprises tunable-focus reference and signal heads **46a-b**. Heads **46a-b** are situated on opposite sides of medium **22**, facing opposite planar input surfaces **50a-b** of medium **22**. Reference head **46a** focuses reference beam **30a** at a storage location **52** within medium **22**, while signal head **48b** focuses signal beam **30b** at storage location **52**.

Heads **46a-b** comprise respectively high numerical aperture (N.A.) objective lenses **48a-b** facing medium **22**, dynamic aberration compensators **39a-b** in the light path between light source **34** and objective lenses **48a-b**, optical detectors **58a-b**, and beam separation components **38a-b** for directing beams **30a-b** toward medium **22** while directing light traveling from medium **22** toward detectors **58a-b**, respectively.

Each of objective lenses **48a-b** typically has a N.A. higher than 0.25, preferably higher than about 0.4, and more preferably about 0.5. High numerical apertures are desirable since they allow relatively short depths of field, and consequently relatively close interhologram spacings along the depth of the medium. High numerical apertures also allow relatively small spot sizes for stored holograms. Increasing numerical apertures

above about 0.5 or 0.6 may lead to substantially increased complexity in the optics required for storage and retrieval, and to relatively stringent tolerances on mechanical components.

Lenses **48a-b** are mounted on dual-axis actuators **47a-b** respectively, which dynamically control the focusing and fine-tracking positions of lenses **48a-b** relative to medium **22**. The focusing actuators control the vertical (in-depth) motion of lenses **48a-b** relative to medium **22**, both coarsely for accessing different depth layers and finely for maintaining lenses **48a-b** focused on a desired depth layer. Coarse and fine tracking positioning is performed along the radial direction of medium **22**, i.e. across tracks **23**. At least one of lenses **48a-b** is further mounted on a track-position actuator. The track-position actuator controls the relative positions of lenses **48a-b** along a track direction (perpendicular to the fine-tracking and focusing directions) to ensure that beams **30a-b** are aligned along the track and are coincidentally focused.

Heads **46a-b** are preferably in a master-slave relationship. For example, if head **46a** is the master head, it focuses beam **30a** on a desired storage location. Control electronics receive position information from head **46a**, and drive head **48b** (the slave head) to follow head **46a**, such that beam **30b** is focused coincidentally with beam **30a**. Master-slave connections and associated electronics are generally well known for electromechanical devices. In general, both heads **46a-b** can be independent master heads for at least some alignment axes, and can be used to coincidentally focus beams **30a-b** independently.

Dynamic aberration compensators **39a-b** dynamically compensate for the variable spherical aberration introduced in beams **30a**, **30b** by medium **22**. The spherical aberration in each beam depends on the depth accessed by the beam. Aberration compensators are generally well known. Various dynamic aberration compensators have been described for conventional pit-based storage, for example in U.S. Patent No. 5,202,875 (Rosen et al). While aberration compensators **39a-b** are shown for clarity as separate from objective lenses **48a-b** and focusing actuators **47a-b**,

aberration compensators **39a-b** may be integrated with lenses **48a-b**.

Preferably, system **20** uses a pure-amplitude modulation scheme. For a system using phase or phase-and-amplitude modulation, a phase shifter **57** in an optical path between light source **34** and medium **22** can be used to introduce a phase delay into beam **30a** and thus vary the relative phase relationships of beams **30a**, **30b**. Phase-shifter **57** is then dynamically controllable and capable of introducing desired phase delays for individual microholograms. An electro-optic modulator is a particularly useful phase shifter. Other potentially suitable phase shifters include piezo-electric mirrors or other well known devices.

The system of Fig. **1-B** can be used for retrieval, with at least one of beams **30a** and **30b** turned on. During retrieval, both beams **30a-b** can act as reference beams. Accessing a stored reflection microhologram with beam **30a** generates a reflected, reconstructed output signal beam **33a**. Beams **30a** and **33a** are counterpropagating. Similarly, accessing data with beam **30b** results in a reflected, reconstructed output signal beam **33b** counterpropagating with beam **30b**. Beam separation components **38a-b** are used to separate the counterpropagating beams. Beam separation components **38a-b** are conventional. Beam separation components **38a-b** comprise polarizing beam splitters (PBS) **54a-b** and quarter-wave plates **56a-b** situated in the optical paths of reference beam **30a** and signal beam **30b** respectively, between light source **34** and head system **40**. Polarizing beam splitters and quarter wave plates are used instead of simple beam-splitters for reducing losses at the separation elements. A switch **59** in an optical path between light source **34** and medium **22** can be used to shut off beam **30b** during data retrieval. Switch **59** can be a mechanical shutter.

Reconstructed output beams **33a-b** are incident on confocal, depth-selective optical detectors **58a-b**, respectively. Detectors **58a-b** comprise spatial filtering optics for allowing detectors **58a-b** to selectively access only storage locations at desired depths within medium **22**. Spatial filtering optics are well known. The spatial filtering optics preferably include

appropriately placed pinholes for selectively allowing only rays reflected from an accessed storage location to be directed to detectors **58a-b**. The pinholes block stray light from non-accessed regions of medium **22**, which would otherwise be incident on detectors **58a-b**.

Fig. **1-C** shows a preferred retrieval system **120** of the present invention. System **120** is similar to system **20**, but does not require separate heads for the signal and reference beams. A single retrieval head **46a** focuses reference beam **30a** on reflection microholograms within medium **22**, and captures a reconstructed output signal beam **33a** resulting from the reflection of reference beam **30a** by the holograms. Reconstructed output beam **33a** is incident on detector **58a**.

Reflection Microholograms

Fig. **2-A** illustrates a preferred reflection microhologram **62** stored at a coinciding focus **60** of reference beam **30a** and signal beam **30b**. Preferably, not more than one microhologram is stored at the location of microhologram **62**. Hologram **62** has substantially planar fringes at focus **60**, parallel to the depth direction of medium **22**. The grating frequency of hologram **62** is approximately twice the frequency of beams **30a**, **30b** within medium **22**. The fringes of hologram **62** are parallel only along a small fraction of the total depth of medium **22**. Away from focus **60**, the fringes of hologram **62** are increasingly curved and weaker. Perfect Bragg-matching a readout reference beam to hologram **62** requires accessing hologram **62** with a light beam identical to reference beam **30a** or signal beam **30b**. Small deviations from perfect Bragg-matching continue to allow readout of hologram **62** if the accessing beam is sufficiently Bragg-matched to hologram **62**. The lack of efficient signal reconstruction in the absence of Bragg-matching allow the storage of holograms at multiple depths.

Since its fringes are substantially parallel to the direction of motion of medium **22**, hologram **62** can be stored and/or retrieved while medium **22** is rotating. For a numerical aperture of about 0.5 and wavelength of about 500 nm, hologram **62** has on the order of tens of fringes within the Rayleigh range of a corresponding

Bragg-matched reference beam. Hologram **62** is thus relatively tolerant to shrinkage within medium **22**, wavelength shifts of light source **34**, and phase drifts in light source **34**, as compared to holograms containing a larger number of fringes.

Generally, the information of hologram **62** is stored as a micro-localized variation in the complex (i.e. real and/or imaginary) index of refraction within medium **22**. Hologram **62** is preferably a phase hologram, i.e. its amplitude characterizes local variations in the real component of the index of refraction of medium **22**. Alternatively, hologram **62** may be an absorption hologram, i.e. its amplitude may characterize local variations in absorption properties within medium **22**. Hologram **62** stores information in its amplitude and/or phase. The index variation of hologram **62** can be represented as a complex function, characterized by an amplitude and a phase. Holograms **62** preferably has one of a set of discrete (digital) amplitude/phase levels.

Hologram **62** is preferably stored at the diffraction limit of high-N.A. optics. Hologram **62** extends over a depth of less than a few tens of microns (e.g. <30 μm), preferably about 10 μm. The depth of hologram **62** is preferably defined by the Rayleigh range of beams **30a-b**. Hologram **62** has a spot (in plane) size of less than a few microns (e.g. <3 μm), preferably about 1 μm x 1 μm. A hologram length of 1 μm corresponds to a readout time of tens of ns for a medium speed of tens of m/s. The spot size may limit the minimal intertrack spacing, as well as the data density along a track. Adjacent tracks are preferably spaced by a distance at least on the order of the hologram spot size, preferably at least about 1 μm. Adjacent holograms along a track are also separated by a distance at least on the order of the hologram spot size. As indicated, a reflection hologram occupies a relatively small volume.

Fig. **2-B** shows a side sectional view through medium **22**, illustrating a typical relative arrangement of microholograms in depth. Multiple planar layers **66** of microholograms are stacked along the depth of medium **22**. Adjacent layers are separated by a distance on the order of the hologram depth or depth of focus

of the accessing beams, preferably about 10 μm center-to-center. The interlayer spacing may vary in depth.

For simplicity, the combined reference and signal beams used to store reflection microholograms **62**, **62'** are denoted as light beam **31**. Holograms **62**, **62'** are situated in different (e.g. adjacent) layers. When light beam **31** is focused at the location of hologram **62**, the out-of-focus parts of light beam **31** also illuminate the storage location of hologram **62'**. The out-of-focus light used for accessing the location of hologram **62**, even though of a relatively low intensity, can reduce the dynamic range of index changes and diffraction efficiencies achievable at the storage location of hologram **62'**.

The degradation of optical properties at one location due to data storage at other locations within medium **22** can be characterized by the "scheduling loss" of the system. Scheduling losses can limit the number of hologram layers that may be stacked. In an optically linear material, the maximum index change at a location varies inversely with the cumulative intensity of light that has contaminated that location. The diffraction efficiency generally varies as the square of the maximum index change. If N layers are written using identical light intensities, the maximum index change in each layer varies as $1/N$, while the diffraction efficiency of stored data varies as $1/N^2$. Scheduling losses can be reduced by offsetting vertically-adjacent tracks or holograms in the radial direction, such that holograms in adjacent depth layers are not vertically aligned. Scheduling losses can also be reduced through the use of an optically non-linear storage material.

The degradation in the optical properties of the location of hologram **62'** due to the storage of hologram **62** may depend on whether hologram **62'** is stored before or after hologram **62**. Therefore, an optimized storage sequence can be designed to minimize optical response degradation within medium **22**. The storage sequence specifies the order of the depths to be accessed during storage.

A system of the present invention can allow a significant improvement in signal-to-noise ratio (SNR), relative to an index-perturbation system using an identical maximal variation in refractive index. The SNR of each system is directly related to the diffraction efficiency of a stored hologram or perturbation. Estimates of diffraction efficiencies for index perturbation and holographic storage methods can be calculated for perturbations and holograms written using plane waves. The mean diffraction efficiency for an index perturbation written with plane waves is approximately

$$\eta \approx \left(\frac{\Delta n}{2n}\right)^2, \qquad [2]$$

for small $\Delta n/n$, where Δn is the index perturbation and n is the index of refraction of the material. By contrast, the diffraction efficiency for a phase reflection hologram written with plane waves is approximately

$$\eta = \tanh^2\left(\frac{\pi d \Delta n}{\lambda}\right) \approx \left(\frac{\pi d \Delta n}{\lambda}\right)^2. \qquad [3]$$

where Δn is the index change in the material, d is the hologram depth (thickness), and λ is the wavelength of the signal and reference beams.

For a Δn of 10^{-3} and $n = 1.5$, eq. [2] yields a diffraction efficiency on the order of 10^{-6} for an index perturbation storage method. For an identical Δn of 10^{-3} and values of d Å 25 μm and λ Å 0.5 μm, equation [3] yields a diffraction efficiency on the order of 10^{-1} for a holographic storage method of the present invention, five orders of magnitude higher than for an index perturbation method using an identical Δn.

Alternative Storage and Readout Schemes

The microholograms can be stored using amplitude, phase, or combined amplitude-and-phase modulation of reference beam **30a** and signal beam **30b**. Because of the simplicity of the required components, pure amplitude modulation is preferred. In amplitude modulation, bits are stored as amplitudes of

corresponding holograms. Modulation and error-correction codes can be used; various such codes are well known.

In pure phase modulation, data can be stored as relative phases of holograms. Fig. **3-B** illustrates schematically holograms **65**, **65'** having opposite phases. The phase of hologram **65'** is offset by π (180°) relative to the phase of hologram **65**. During storage, at least one of beams **30a**, **30b** can be phase delayed to produce a relative phase delay of π between the storage of holograms **65**, **65'**. During readout, the reconstructed signal beam from each hologram can be compared to a phase reference. The signal detected by detector **58a** then depends on the phase difference between the phase reference and the signal beam from the stored hologram. For example, a phase reference can interfere constructively with the signal reflected from one of holograms **65**, **65'**, and destructively with the signal reflected from the other.

Parallel readout can be accomplished by using a light source comprising a plurality of mutually incoherent lasers aligned in close proximity. The lasers generate spatially separated. mutually incoherent reference beams. The reference beams are imaged onto a radial line such that each reference beam is focused on one of a number of adjacent tracks within the medium. A detector comprising multiple independent aligned detecting elements is then used for data retrieval. Each of the reconstructed output beams is incident on one of the detecting elements. Since the reference beams are mutually incoherent, they do not interfere even if their corresponding tracks are closely spaced.

In general, various head-arm assemblies may be used in a system and method of the present invention. Fig. **4** illustrates a rotary head-arm assembly **16** that may be used in the present invention. Rotary geometries are conventionally used in magnetic storage systems. Arm assembly **16** comprises rigid arms **18a-b** controlled by a rotary actuator. Objective lenses **48a-b** (not shown) are mounted at distal ends **19a-b** of arms **18a-b**. Arms **18a-b** can be used for coarse tracking positioning of lenses **48a-b** relative to medium **22**.

It will be clear to one skilled in the art that the above embodiments may be altered in many ways without departing from the scope of the invention. For example, the distinction between the reference and signal beams during storage is a formal one, since information is encoded in the amplitude and/or phase of the beams rather than necessarily in the wave structure (cross-sectional pattern) of the signal beam. The signal and reference beams are essentially equivalent during storage, and any of the two beams may be used for retrieval. Multiple discrete amplitude/phase levels for the microholograms may be used for digital gray scale storage. Continuous levels may be used for analog storage.

The holograms need not be uniform round spots. As the disk continuously rotates, a continuous hologram can be written, and the intensity of the writing beam can be varied in time to store information as micro-localized variations in the hologram according to a suitable modulation code. Such storage and readout in a moving medium would be facilitated by the planar orientation of the hologram fringes, in the plane of the disk. Various modulation codes which relate stored information to a complex-valued temporal waveform (i.e. an amplitude and/or phase function) characterizing a reflection hologram can be used.

Various track arrangements, both in plane and in depth, can be used. Such arrangements include, by way of example and not necessarily by way of limitation: stacked in-plane spiral arrangements, a three-dimensional spiral extending throughout the entire medium, or a 3-D cartesian array. Spirals are generally well suited for extended recording and playback of audio and/or video, and are commonly used in CD and DVD technology. Concentric tracks are generally well suited for uses where rapid random access is more common, such as for computer data storage. Holograms can be stored in a variety of other arrangements at a plurality of depths in the medium.

The storage medium need not be disk-shaped; data may be stored in a cartesian geometry, with the heads controlled by x-y stages. The storage medium may be moved relative to vertically-

fixed heads to bring different depths in focus. The storage medium need not be packaged in a disk-like storage device. Various other storage devices (e.g. cartridges or cards) may be suitable. Various mounting and actuating (e.g. rotary/linear, horizontal and vertical) arrangements for the heads may be suitable. Various types of lasers can be used as light sources, including diode, solid state, and other types of lasers. The light source may include a non-linear frequency-converter in addition to a laser.

The storage material can be in general any suitable linear or non-linear photosensitive material. The storage medium material need not be a photopolymer. For example, various storage materials known in the art can be suitable for the present invention, including photopolymers, photosensitive glasses, and photorefractive materials. A non-linear medium such as a two-photon medium can be used, in which light incident on the medium at one wavelength sensitizes the medium for recording at another wavelength. The use of a non-linear storage material may reduce scheduling losses that occur in linear media.

It will be apparent from the foregoing that, while particular forms of the invention have been illustrated and described, various modifications can be made without departing from the spirit and scope of the invention. Accordingly, it is not intended that the invention be limited, except as determined by the following claims and their legal equivalents.

CLAIMS

What is claimed is:

1. A holographic digital data storage system comprising:
   a) a holographic storage medium;
   b) a light source for generating a signal beam and a reference beam;
   c) a tunable-focus reference head in optical communication with said light source and facing said medium, for focusing said reference beam at storage locations at a plurality of depths within said medium; and
   d) a tunable-focus signal head in optical communication with said light source and facing said medium opposite said reference head, for focusing said signal beam coincidentally with said reference beam in a substantially counterpropagating geometry at said storage locations, for storing digital data as reflection microholograms at said storage locations.

2. The system of claim 1 wherein said storage locations are situated within a homogeneous photopolymer layer of said medium.

3. The system of claim 1 further comprising a first aberration compensator positioned between said light source and said reference head, for compensating for a depth dependence of a spherical aberration of said reference beam, and a second aberration compensator positioned between said light source and said signal head for compensating for a depth dependence of a spherical aberration of said signal beam.

4. The system of claim 1 further comprising a phase shifter in an optical path between said light source and said medium, for controlling a relative phase relationship of said reference beam and said signal beam.

5. The system of claim 4 wherein said phase shifter controls said relative phase relationship such that adjacent reflection microholograms along a track of said medium have substantially opposite phases.

6. The system of claim 1 wherein at least one of said reference head and said signal head further comprises a track-position actuator for controlling a relative position of said reference beam and said signal beam along a track of said medium, for ensuring that said reference bean and said signal beam are coincidentally focused.

7. The system of claim 1 wherein said holographic storage medium is selected from the group consisting of disk-shaped media, cartridge-shaped media and card-shaped media.

8. A holographic digital data storage system comprising:

a) a holographic storage medium;

b) a light source for generating a signal beam and a reference beam; and

c) a tunable-focus storage head system in optical communication with said light source and facing said medium, positioned to coincidentally focus said signal beam and said reference beam in a substantially counterpropagating geometry at storage locations at a plurality of depths within said medium, for storing digital data as reflection microholograms at said storage locations.

9. The system of claim 8 wherein said holographic storage medium is selected from the group consisting of disk-shaped media, cartridge-shaped media and card-shaped media.

10. A holographic digital data retrieval system comprising:
   a) a holographic storage medium;
   b) a light source for generating a reference beam;
   c) a tunable-focus retrieval head in optical communication with said light source and facing said medium, for focusing said reference beam on reflection microholograms at a plurality of depths within said medium, and for capturing a signal beam reflected by said reflection microholograms; and
   d) an optical detector in optical communication with said retrieval head, for detecting said signal beam to retrieve digital data stored as said reflection microholograms.

11. The system of claim 10 wherein said storage locations are situated within a homogeneous photopolymer layer of said medium.

12. The system of claim 10 further comprising a dynamic aberration compensator in an optical path between said light source and said retrieval head, for dynamically compensating for a depth dependence of spherical aberrations of said reference beam and said signal beam.

13. The system of claim 10 wherein said light source comprises a plurality of lasers for generating a corresponding plurality of mutually incoherent reference beams, for simultaneously accessing multiple data tracks within said medium with said reference beams.

14. The system of claim 10 wherein said holographic storage medium is selected from the group consisting of disk-shaped media, cartridge-shaped media and card-shaped media.

15. An optical data storage device comprising a layer of holographic storage medium having data stored as reflection microholograms at a plurality of depths therein.

16. The device of claim 15 wherein said reflection microholograms are arranged in at least five layers at corresponding depths in said medium.

17. The device of claim 15 wherein adjacent reflection microholograms in said medium have substantially opposite phases.

18. An optical data storage device comprising a holographic storage medium having data stored therein, said data being in the form of micro-localized variations in a complex index of refraction characterizing reflection holograms at a plurality of depths in said medium.

19. The device of claim 18 wherein said holographic storage medium is selected from the group consisting of disk-shaped media, cartridge-shaped media and card-shaped media.

20. A holographic data storage system comprising:
a) a holder for a holographic storage medium; and
b) optics mechanically connected to said holder, positioned to direct a reference beam and a signal beam onto said medium, for storing data as micro-localized variations in a complex index of refraction characterizing reflection holograms at a plurality of depths in said medium.

21. A holographic data storage system comprising:
a) a holder for a holographic storage medium; and
b) optics mechanically connected to said holder, positioned to direct light onto said medium for storing data as micro-localized variations in a complex index of

refraction characterizing reflection holograms at a plurality of depths in said medium.

22. A holographic data retrieval system comprising:
a) a holder for a holographic storage medium; and
b) optics mechanically connected to said holder, positioned to direct a reference beam onto said medium, for retrieving data stored as micro-localized variations in a complex index of refraction characterizing reflection holograms at a plurality of depths in said medium.

23. A holographic digital data storage system comprising:
a) a holographic storage medium;
b) optics for generating a signal beam and a reference beam; and
c) a tunable-focus storage head system in optical communication with said optics, positioned to focus said signal beam and said reference beam at a plurality of storage locations within said medium, for storing digital data as reflection microholograms at said storage locations.

24. The system of claim 23 wherein said tunable-focus storage head system is positioned to coincidentally focus said signal beam and said reference beam in a substantially counterpropagating geometry from opposite sides of said medium.

25. The system of claim 23 wherein said holographic storage medium is selected from the group consisting of disk-shaped media, cartridge-shaped media and card-shaped media.

26. A holographic digital data storage method comprising the steps of:

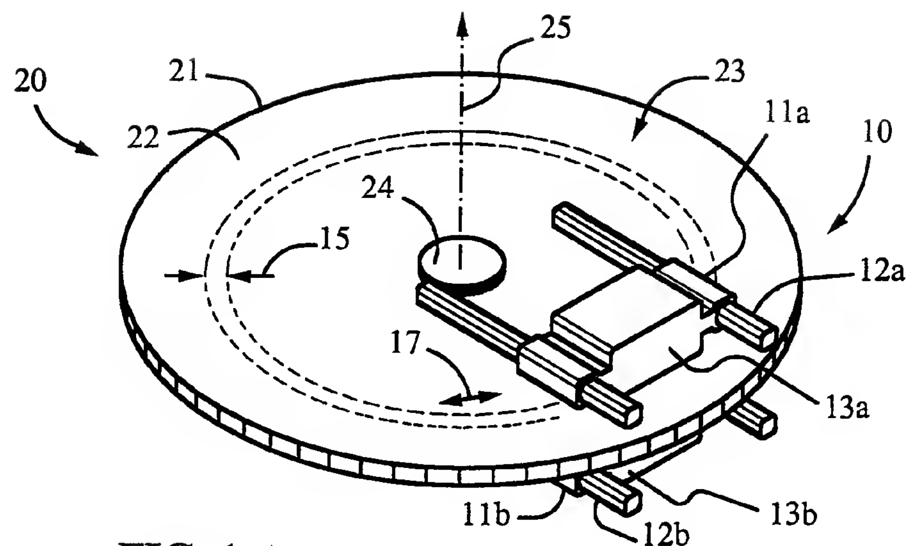
a) focusing a reference beam at storage locations at a plurality of depths within a holographic storage medium; and

b) focusing a signal beam coincidentally with said reference beam in a substantially counterpropagating geometry at said storage locations, for storing digital data as reflection microholograms at said storage locations.

27. A holographic digital data retrieval method comprising the steps of:

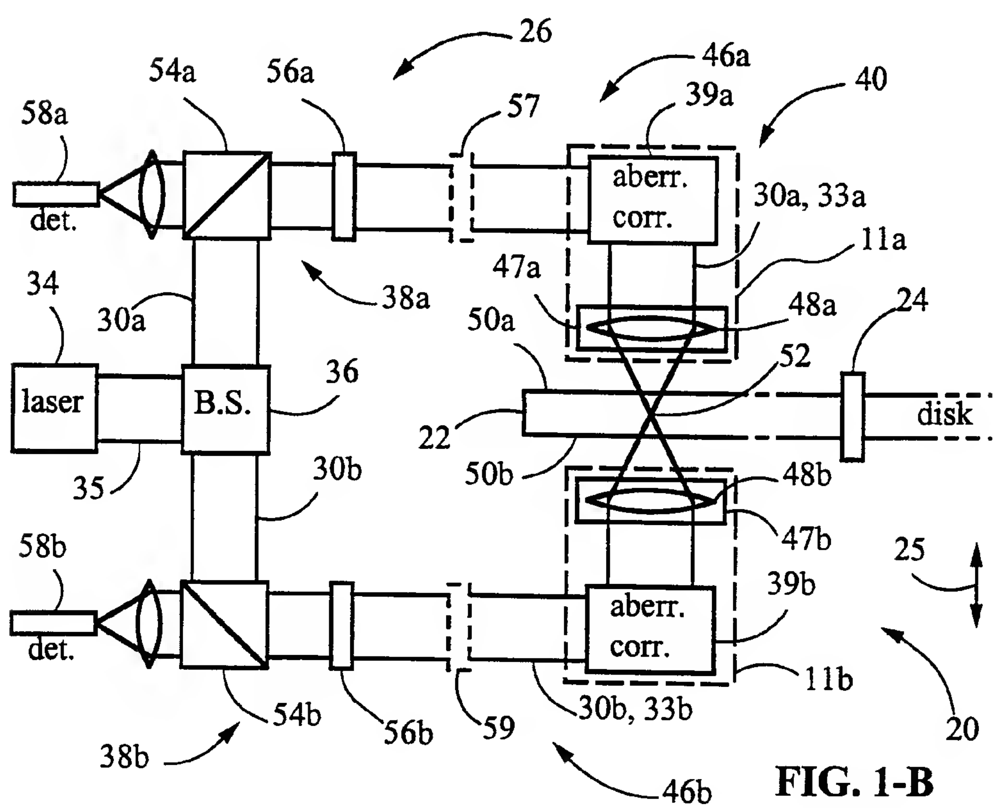
a) focusing a reference beam on reflection microholograms at a plurality of depths within a holographic storage medium; and

b) detecting a signal beam reflected by said reflection microholograms to retrieve digital data stored as said reflection microholograms.



25
20
21
23
11a
10
22
24
15
12a
17
13a
11b
12b
13b

FIG. 1-A



26
46a
40
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56a
39a
58a
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aberr.
corr.
30a, 33a
det.
11a
34
30a
38a
47a
48a
24
50a
36
52
laser
B.S.
disk
22
35
50b
48b
30b
47b
58b
25
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corr.
det.
11b
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56b
59
30b, 33b
20
38b
46b

FIG. 1-B

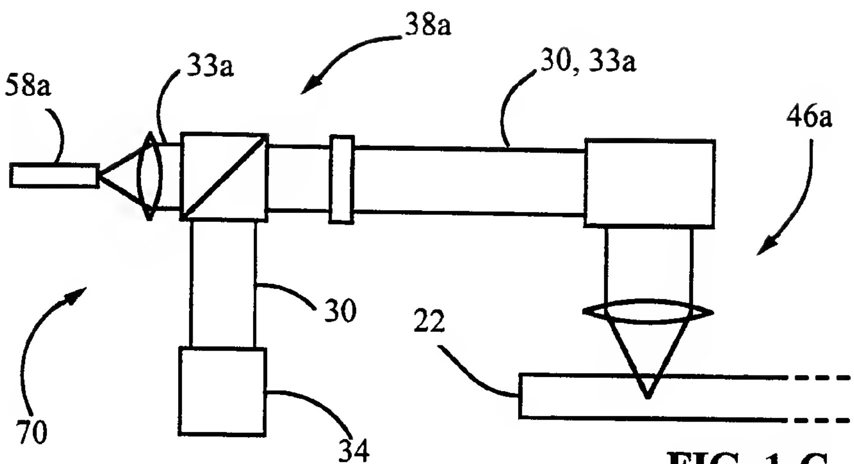

FIG. 1-C

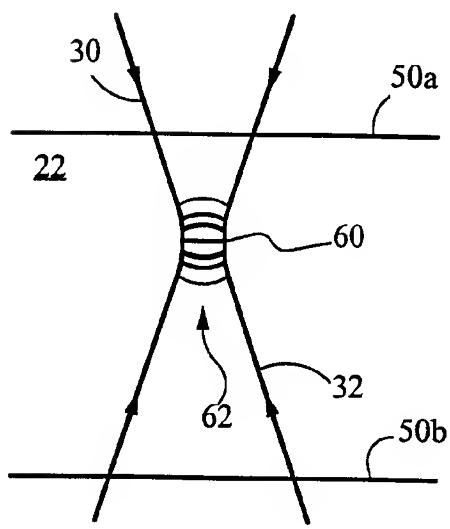

FIG. 2-A

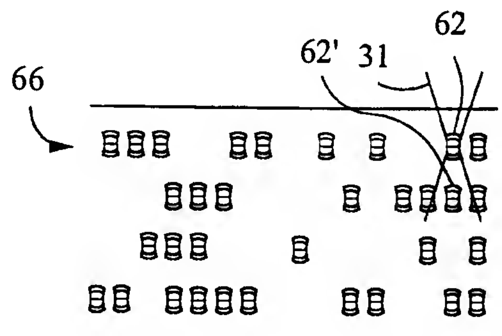

FIG. 2-B

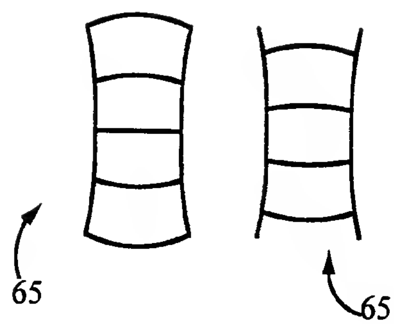

FIG. 3

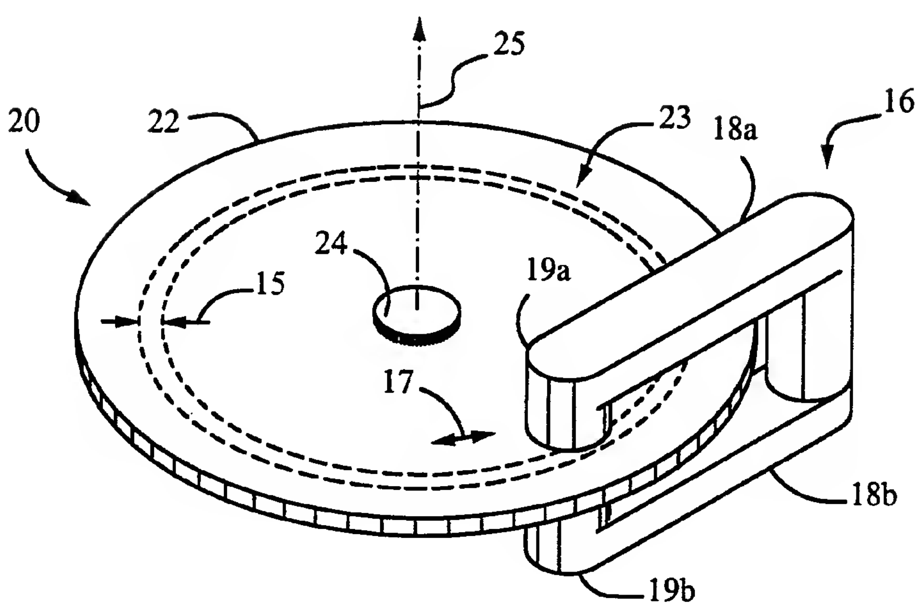

FIG. 4

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/01763

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G11B 7/00; G03H 1/26
US CL :369/44.23, 103, 109, 112, 122: 359/3, 22, 35
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 359/1, 4, 7, 24, 25; 365/125, 234, 235

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,283,777 A (Tanno et al) 01 February 1994 (01.02.94), see entire document.	1-27
Y	US 4,458,345 A (Bjorklund et al) 03 July 1984 (03.07.84), see entire document.	1-27
P	US 5,737,294 A (Yamakawa et al) 07 April 1998 (07.04.98), see entire document.	1-27
Y	US 5,202,875 A (Rosen et al) 13 April 1993 (13.04.93), see entire document.	3
Y	US 4,318,581 A (Guest et al) 09 March 1982 (09.03.82), see entire document.	5,17

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
24 MARCH 1999	22 APR 1999

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Form PCT/ISA/210 (second sheet)(July 1992)★